Quantifying Effects of Mid-Frequency Sonar Transmissions on Fish and Whale Behavior

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LONG-TERM GOALS

There are two high-level goals: to understand and quantify effects of mid-frequency (MF) sonar on fish and whale behavior through direct observation, and to investigate the potential usefulness of MF sonar in acoustic measurements of fish, including stock assessments.

OBJECTIVES

The initial objectives are to prove the usefulness of the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar for observing fish in the water column, and to establish protocols for calibrating the difference-frequency band of this sonar. The TOPAS parametric sonar will then be used as a mid-frequency (MF) sound source, with the aim of collecting data on herring *in situ* in the Norwegian Sea and *ex situ* in pens at the Austevoll Aquaculture Research Station. The data will be analyzed to determine possible behavioral responses of herring to MF sonar transmissions. Ultimately it is the aim to integrate acoustic data on herring with independently collected tagging data from whales to quantify behavioral effects of MF sonar.

APPROACH

This project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting a series of sound-exposure experiments at sea to observe the behavioral response of whales and Atlantic herring (*Clupea harengus*) to mid-frequency (MF) sonar transmissions. The sources of the MF sonar signals are the new, Norwegian, Nansen-class frigate sonar, with operating band 1-8 kHz, and the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar, with primary frequency band 15-21 kHz and difference-frequency band 0.5-6 kHz. The IMR project is entitled "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS.

The approach is intended to augment the Norwegian LowFreq Project in a number of ways. These are arranged by task.

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Task 1. Observation of herring by parametric sonar. The PI, K. Foote, is participating on cruises with Norwegian research vessels to observe Norwegian spring-spawning herring *in situ*, especially during the wintering period off the northwest coast of Norway. The first aim of this work is to establish the acoustic detectability of herring with the TOPAS parametric sonar difference-frequency band, which was proposed by the PI to IMR colleagues in 2003. Given measureable echoes, the second aim is to establish the quantifiability of herring by the same difference-frequency band, including measurement of numerical density and sizing based on excitation of swimbladder resonance. The PI will participate in analyses of the data, especially through application of calibration data (Task 2) and developed range compensation functions (Task 3).

Task 2. Development of standard-target calibration protocols for parametric sonar. The PI will lead development of these protocols, already commenced through the design of a standard target for calibration of the difference-frequency band of TOPAS, namely a 280-mm-diameter solid sphere of aluminum alloy (Foote et al. 2007). It is noted that measurement of fish in the upper water column will be made in the TOPAS nearfield, where the difference-frequency wave is being formed, hence the calibration measurements will be made at several ranges. In addition, the high directionality of the difference-frequency wave will require precise target positioning in the transducer beam, which can be accomplished by using an auxiliary sonar operating at an ultrasonic frequency. The PI will participate in the initial calibration trials in the Norwegian Sea, and participate in the analysis of forthcoming data, providing necessary guidelines.

Task 3. Development of range compensation functions for parametric sonar. Range compensation refers to the process whereby the range dependence of echoes, due to geometrical and absorption effects, is removed so that the resulting quantity depends only on the acoustic properties of the targets and their position in the transmit and receive beams of the observing sonar. The PI will develop range compensation functions, called time-varied gain (TVG) functions when applied electronically (Medwin and Clay 1998), for use in measuring the target strength (TS) of resolvable single targets and the volume backscattering strength (S_v) of dense layers of targets, hence of herring in states of relative dispersion and dense aggregation, respectively. For conventional sonars, two range compensation functions are particularly useful. For TS measurements, the echo strength in the logarithmic domain is increased by adding the quantity $40 \log r + 2\alpha r$, where r is the target range, typically expressed in meters, and α is the absorption coefficient, typically expressed in decibels per meter. For S_v measurements, the echo strength is increased by adding the quantity $20 \log r + 2\alpha r$. The situation is more complicated for sonars in which measurements are made in the nearfield of the transmit array. This is the case for the TOPAS parametric sonar when applied to fish in the upper water column, for the difference-frequency signal is literally being formed at ranges where backscattering is being measured. It is noted that significant TOPAS echoes are invariably received in the farfield of the transducer array used for reception.

Task 4. Use of parametric sonar as a sound source in the MF sonar band. The PI will participate in cruises to observe the behavior of herring *in situ* during the wintering period and *ex situ* in pens to determine the possible presence and magnitude of effects due to the exposure of the herring to MF sound generated by the TOPAS parametric sonar. The PI will participate in analyses of the *in situ* data.

Task 5. Integration of parametric sonar data on herring behavior with other sound exposure data on herring and whale behavior. When other sound-exposure data become available, the PI will participate in the integration of the TOPAS parametric sonar data in an assessment of the overall effects of MF

sound on fish and whale behavior. The other sound-exposure data are expected to include measurements made with the new, Norwegian frigate sonar, and observations derived from tags attached to whales in areas where the whales are feeding on fish.

WORK COMPLETED

Task 2: During the calibration trial conducted with R/V "G. O. Sars" in the Sørfolla fjord, near (67 31'N, 15 24'E), on 10 December 2008, a standard target was observed with the Simrad EK60 scientific echo sounder (Foote et al. 2009). Accurate positioning of the target in the difference-frequency beam of the TOPAS parametric sonar is essential. Use of the split-beam functionality of the EK60 enabled the position of the target to be determined ping by ping. Since the target was moving, owing to the depths of suspension, nominally 90, 225, and 330 m, the split-beam data enabled the target to be tracked. Earlier work considered the two lowest frequencies of the echo sounder, namely 18 and 38 kHz (Foote et al. 2010). During this reporting year, the analysis has been extended to 70, 120, and 200 kHz for the 90-m range. The angular position of the target is being characterized by each of four quantities. These involve the raw split-beam data, which measure the alongship and athwartship angles, and the polar and azimuthal angles expressed in the coordinate system with origin at the center of the TOPAS transducer. Four linear measures of position are also being considered: the range and three rectangular coordinates of the target, all referred to the center of the TOPAS transducer. Statistical comparisons have been performed for pairs of frequencies based on the raw or transformed position data. This has been done both without any constraint and with restriction of the magnitudes of the raw split-beam angles to 3.5 deg. This is the central part of all beams, since the full beamwidth at 18 kHz is 11 deg and that at the higher frequencies is 7 deg.

Task 3: Determination of range compensation functions for the particular TOPAS PS18 parametric sonar is essential for its quantitative use. These functions were specified earlier for the general nearfield case (Foote 2009). They were evaluated numerically for both single- and multiple-target backscattering during the previous reporting period, but for a smaller receive array than was actually used during the reported *in situ* measurements in December 2008 and November 2009 (Godø et al. 2009, 2010a). During this reporting period, the functions were evaluated numerically for identical transmit and receive apertures of rectangular dimensions 1100 x 1035 mm in the respective alongship and athwartship directions. As before, the basic computations of the difference-frequency field of the parametric sonar were performed with the CONVOL5 computer code (Moffett 2003), which realizes the algorithms in Mellen and Moffett (1978) and Moffett and Mellen (1981). These algorithms recognize the intrinsic endfire nature of the parameter acoustic array (Westervelt 1963, Foote 2007), but incorporate effects due to the finite aperture of the transmitting array and more general conditions of absorption, including an absorption-limited nearfield. In addition, the respective single- and multiple-target range compensation functions were averaged over the difference-frequency band 1-6 kHz.

Task 4: Comparison of echo recordings of fish aggregations by the TOPAS parametric sonar and EK60 scientific echo sounder enables observation of some fish behavioral reactions. This is due to the expected differential nature of these, and the proximity of the respective transducers on the hull of R/V "G. O. Sars" but with different beamwidths. Earlier this work was based on the EK60 operating frequencies of 18 and 38 kHz (Godø et al. 2010b). It is now being extended to the higher frequencies of the EK60. While these have the same beamwidths as that at 38 kHz, namely 7 deg, the estimates will become more robust. This work is ongoing.

RESULTS

Task 2: To standardize the pairwise comparison for the five EK60 frequencies that were examined, 38 kHz was chosen as a reference. The four angular measures of standard-target position at nominal 90-m range are shown for this frequency in Fig. 1. It is noted that the data, spanning about 4800 s and consisting of approximately 4000 echoes, were essentially noisy. The target was tracked except during periods of spikes, which are almost certainly artificial in the sense of not reflecting the instantaneous target position. In some other cases, the target may have undertaken larger short-terms excursions, but with continuity of movement. The 18-kHz data are compared with the 38-kHz data for the respective angles in Fig. 2. These reveal a difference in noise structure, with the 18-kHz data being noisier, possibly due to the similarity in the overlapping narrow bandwidth of the EK60/18-kHz echo sounder and broad transmit bandwidth of the TOPAS parametric sonar centered at 18 kHz, notwithstanding phasing of the two sonars to avoid direct acoustic interference. The polar and azimuthal angles are compared for each pair of frequencies in Fig. 3. While some noise is frequency-dependent, noise such as spikes may be repeated across all frequencies. These results coupled with the statistical analysis reported in Foote et al. (2011) may suggest specific ways to eliminate the noisy data, ultimately to track the target in the parametric sonar beam with high accuracy.

Task 3: Examples of computed range compensation functions for single and multiple targets in the TOPAS PS18 parametric sonar beam are shown in Fig. 4. The functions are evaluated here at both 2 and 5 kHz, with small differences. Such differences are evident in Fig. 5, where the respective functions are averaged over the frequency band 1-6 kHz, and the extremes at 1 and 6 kHz are presented along with the average.

IMPACT/APPLICATIONS

National Security

Navy operations at sea can be affected by the presence of marine mammals. It is expected that the results of the project will contribute to knowledge of possible effects of MF sonar transmissions on the behavior of whales as well as that of other marine animals, especially including fish.

Economic Development

More general use of MF sonars encompassing both water-column and sub-bottom domains may encourage the application, hence increased production, of such sonars. Parametric sonars are especially attractive in this regard because of their physical compactness relative to the exceptionally narrow beamwidths that they produce at low frequencies.

Quality of Life

Society is concerned about the impact of sonar on marine life. This project is attempting to learn about this impact in a quantitative way, ultimately so that possible adverse effects can be avoided or otherwise mitigated.

Science Education and Communication

Forthcoming results from this project are already being published through the scientific literature and lectures to the public. It is expected that these and other publication and communication activities will contribute to science education, as through academic programs in marine science, as well as to more general science literacy among the interested public.

RELATED PROJECTS

As mentioned in the approach section above, this project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting the project "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS. It is expected that the Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the ONR project in disseminating forthcoming results.

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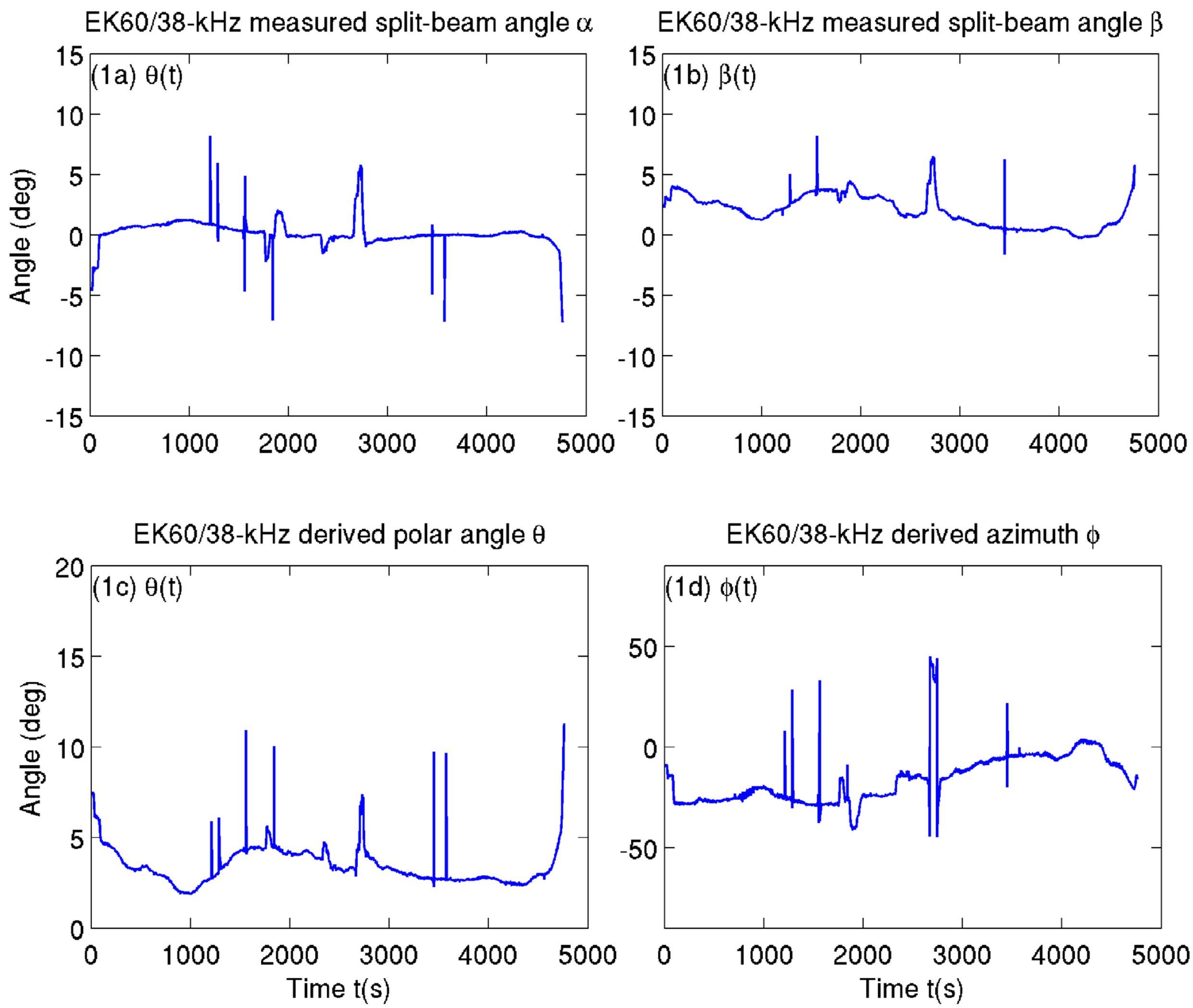

Fig. 1. Times series of four angular measures of position of the standard target at nominal 90-m range as determined with the EK60/38-kHz scientific split-beam echo sounder. (a) Split-beam alongship angle. (b) Split-beam athwartship angle. (c) Polar angle expressed in the coordinate system of the TOPAS transducer, with origin at the transducer center. (d) Azimuthal angle expressed in the same TOPAS coordinates as the polar angle.

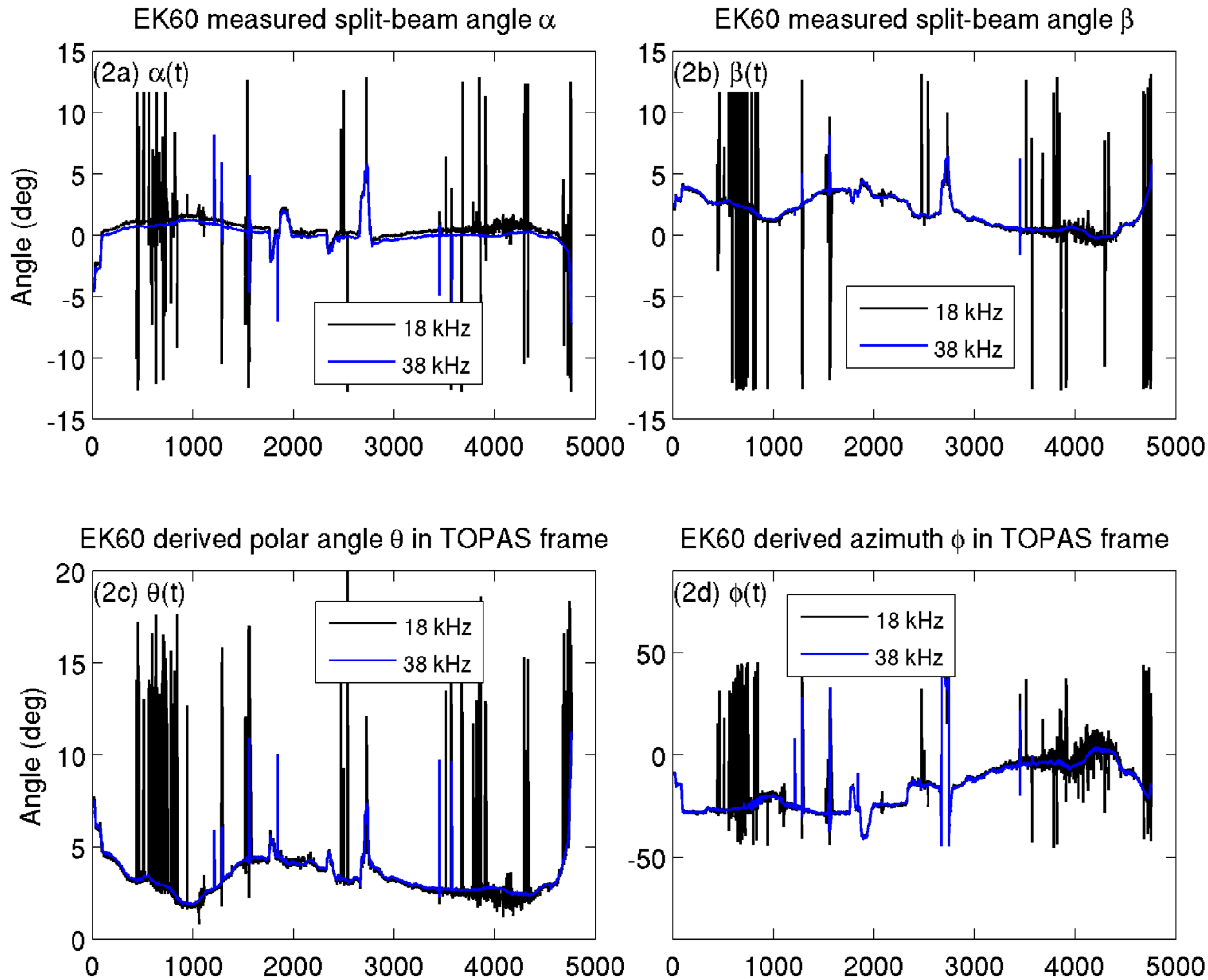

Fig. 2. Paired time series of four angular measures of position of the standard target at nominal 90-m range as determined with the EK60 scientific split-beam echo sounder operating at 18 and 38 kHz. (a) Split-beam alongship angle. (b) Split-beam athwartship angle. (c) Polar angle expressed in the coordinate system of the TOPAS transducer, with origin at the transducer center. (d) Azimuthal angle expressed in the same TOPAS coordinates as the polar angle.

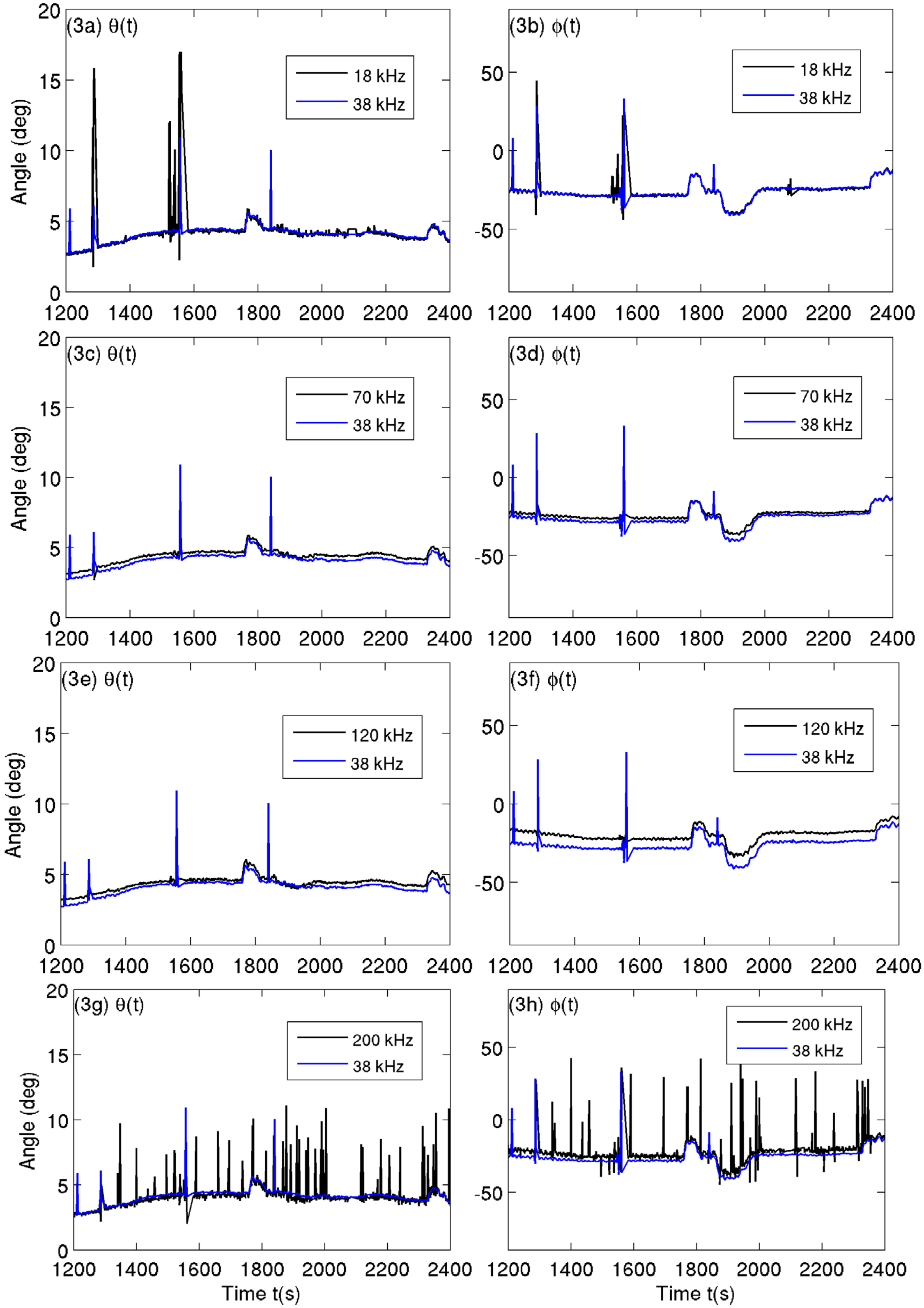

Fig. 3 Time series of angular positions of a standard target in the beam of the TOPAS sonar. The angles θ and φ were derived from simultaneous EK60 split-beam measurements with transducers proximate to the TOPAS transducer and expressed in the reference frame defined by the same.

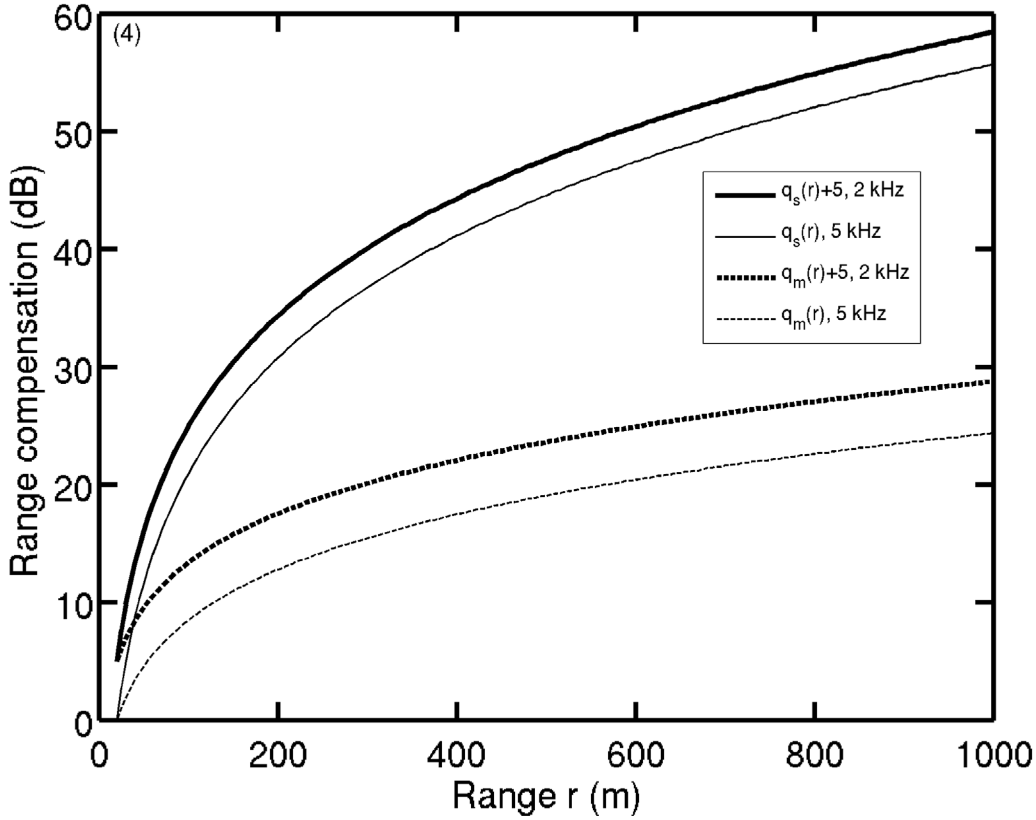

Fig. 4. Range compensation functions for single and multiple targets defined by the respective normalized quantities $q_s(r)$ and $q_m(r)$ for the TOPAS PS18 parametric sonar at the difference frequencies 2 and 5 kHz for the assumed hydrographic state defined by temperature 5ºC, salinity 35 ppt, pH 8, and depth 200 m. To resolve the respective functions, those at 2 kHz have been displaced by 5 dB, as indicated in the legend.

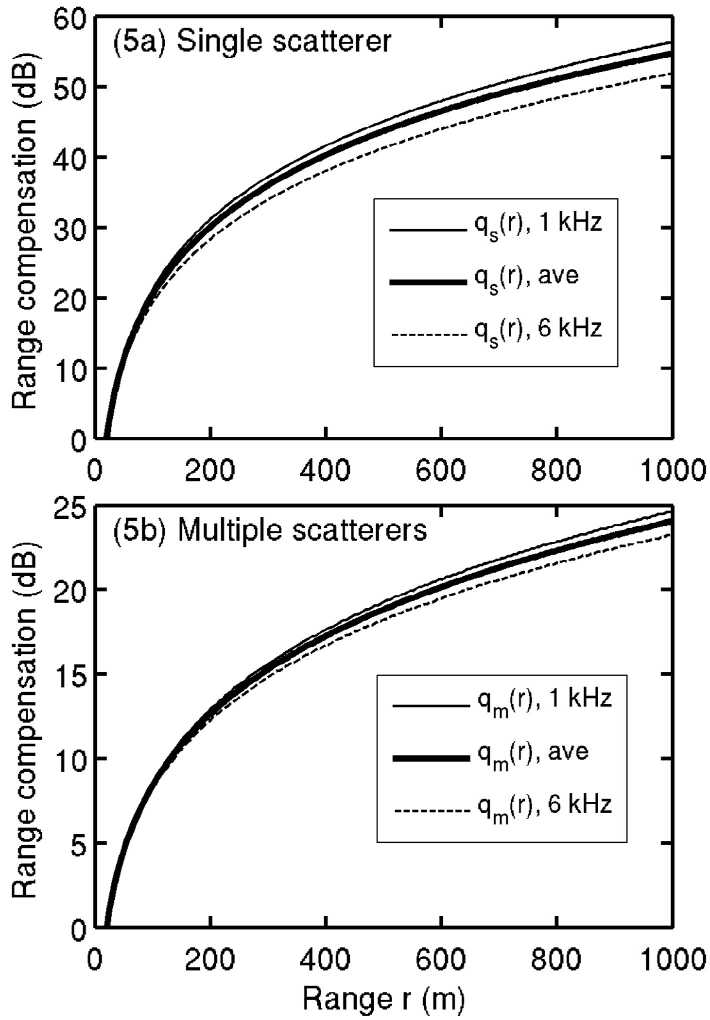

Fig. 5. Band-averaged and limiting range compensation functions for single and multiple targets defined by the respective normalized quantities $q_s(r)$ and $q_m(r)$ for the TOPAS PS18 parametric sonar. The averaging is performed over the difference-frequency band 1-6 kHz resolved at 1-kHz intervals. The dependence of the range compensation function is monotonic with respect to frequency; the limiting functions at the difference frequencies 1 and 6 kHz are shown. The assumed hydrographic state is defined by temperature 5ºC, salinity 35 ppt, pH 8, and depth 200 m.